NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 3054

INVESTIGATION AT SUPERSONIC SPEEDS OF THE WAVE DRAG OF SEVEN BOATTAIL BODIES OF REVOLUTION DESIGNED FOR MINIMUM WAVE DRAG

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SUMMARY

An investigation has been made in the Langley 9-inch supersonic tunnel to determine the effects of varying Reynolds number at each of three Mach numbers upon the wave drag of seven boattail bodies of revolution designed for minimum wave drag according to the method presented in NACA TN 2550. The tests covered a Reynolds number range from approximately 2.0×10^6 to 10.0×10^6 at each of three Mach numbers, 1.62, 1.93, and 2.41. The results show that there was little variation in the pressure distribution with Reynolds number. The experimental wave-drag coefficients were less than the theoretical values and the discrepancy between experiment and theory increased with increasing Mach number, whereas theory predicts no variation of wave drag with Mach number. From a simple analysis, it is seen that the method of NACA TN 2550 is inadequate for determining the shapes of boattail bodies for minimum drag, at least for fineness ratios and Mach numbers of practical interest. However, the bodies of NACA TN 2550 had relatively low experimental wave drag as compared with other boattail body shapes.

INTRODUCTION

The shapes of certain boattail bodies of revolution said to have minimum wave drag were determined by Adams in reference 1 by use of the linearized theory for slender bodies of revolution. The properties of three specific families of bodies were determined and the second family, having fixed length, base area, and maximum area, with a fineness ratio of 8, was found to have the least drag. For this reason the second family of bodies was selected to be investigated.

In an effort to check experimentally the theory of Adams (ref. 1) an investigation was conducted in the Langley 9-inch supersonic tunnel of the zero-lift wave-drag characteristics of seven boattail bodies of revolution having a ratio of base area to maximum area from about 0.1 to 1.0. The measurements included the variation of the pressure distribution and wave drag over a Reynolds number range of approximately 2.0×10^6 to 10.0×10^6 at each of three Mach numbers, 1.62, 1.93, and 2.41.

SYMBOLS

S_{max} maximum body-cross-sectional area

B body-base area

q_o dynamic pressure of free stream, $\frac{\gamma}{2} p_o M^2$

M free-stream Mach number

l body length

d maximum body diameter

x distance along body axis measured from nose of body

C_{D_W} wave-drag coefficient, $\int_0^l P \frac{d}{dx}\left(\frac{r}{r_{max}}\right)^2 dx$

r local body radius

r_{max} maximum body radius

P pressure coefficient, $\frac{p_l - p_o}{q_o}$

p_l local static pressure

p_o free-stream static pressure

R Reynolds number based on body length and free-stream conditions

x/l distance from nose of model in body lengths

γ ratio of specific heats for air (1.4)

APPARATUS

Wind Tunnel

The Langley 9-inch supersonic tunnel is a continuous-operation, closed-circuit tunnel in which the pressure, temperature, and humidity of the enclosed air can be regulated. Different test Mach numbers are provided by interchangeable nozzle blocks which form test sections approximately 9 inches square. Eleven fine-mesh turbulence-damping screens are installed in the relatively large-area settling chamber ahead of the supersonic nozzle. The turbulence level of the tunnel is considered low, based on past turbulence-level measurements. A schlieren optical system is provided for qualitative flow observations.

Models

A drawing illustrating the construction details of the models and giving the pertinent dimensions is shown in figure 1 and a photograph of the models is shown as figure 2. The seven body shapes were determined from the following general equation:

$$S(x') = \frac{B'}{\pi c}\sqrt{1 - x'^2} + \frac{B'}{\pi c}\,\frac{(x' - c)^2}{\sqrt{1 - c^2}}\log_e N + \frac{B'}{\pi}\cos^{-1}(-x')$$

where

$S(x')$ nondimensional body-cross-sectional area, $\pi\,\dfrac{r(x')^2}{(l/2)^2}$

B' body-base area divided by $(l/2)^2$

x' distance made nondimensional with respect to $l/2$ and measured along body axis from midpoint of body c distance, divided by $l/2$, from midpoint of body to location of maximum diameter

$$N = \frac{1 - cx' - \sqrt{1 - c^2}\sqrt{1 - x'^2}}{|x' - c|}$$

The models vary in ratio of base area to maximum area from approximately 0.1 to 1.0 and all models have a fineness ratio of 8. The models were made of stainless steel and at the beginning of each run the model was polished with a metal polish and carefully wiped with a chamois to preserve a uniformity of surface conditions during the tests. The surface roughness of the models was about 8 root-mean-square microinches. Twenty orifices were evenly spaced along the length of each model. The orifice lead tubes were conducted out of the rear of the model within the hollow sting support of each model. The models and their stings were then filled with a sealing material to prevent any leakage.

TESTS

All tests were conducted at Mach numbers of 1.62, 1.93, and 2.41 and over a Reynolds number range of approximately 2.0×10^6 to 10.0×10^6 at each Mach number. Throughout the tests the dew point was kept sufficiently low to insure negligible effects of condensation. A condition of zero pitch and yaw with respect to the tunnel side walls and center line, respectively, was maintained as closely as possible. Pressure-distribution measurements were made over the seven models along the pitch meridian plane. Optical means were employed to check model yaw and model pitch. Pressure measurements were made along one meridian plane only since it has been found that flow deviations within the test section of the tunnel are small. Throughout the test program the models were under schlieren observation.

REDUCTION OF DATA

All experimental pressure data have been corrected to account for the static pressure distribution along the center line of the tunnel test section as measured in the pitch and yaw meridian planes on a long 3/8-inch-diameter cylinder having a slender ogival nose. These measurements covered the range of Mach number and Reynolds number of the present tests. In terms of drag coefficient, the maximum buoyancy correction for any combination of Mach number and Reynolds number was about 0.007, the average correction being about 0.003 or less at $M = 1.62$ and 1.93 and about 0.002 at $M = 2.41$.

PRECISION OF DATA

All models were maintained to within $\pm 0.15^{\circ}$ of zero pitch and yaw with respect to the tunnel side walls and center line, respectively. The estimated accuracies of the test variables and the measured coefficients are given for a tunnel stagnation pressure of 30 in. Hg corresponding to a Reynolds number of approximately 2.5×10^{6}:

Mach number, M . . . . ± 0.01
Reynolds number, R . . . . $\pm 0.004 \times 10^{6}$ per inch
Pressure coefficient, P . . . . ± 0.002
Wave-drag coefficient, C_{D_W} . . . . ± 0.002

RESULTS AND DISCUSSION

Pressure Distributions

The results of the pressure-distribution measurements are presented in figure 3. In general, it is seen that the pressure distributions vary little with Reynolds number. Figure 3 indicates a noticeable positive pressure gradient over the rear of the bodies which appears to begin just behind the maximum thickness; consequently, as B/S_{max} increases (S_{max} moving toward the base), this pressure gradient covers a smaller percentage of the afterbody until at $B/S_{max} = 1$ it is completely eliminated.

Wave Drag

The values of wave-drag coefficient C_{D_W} are presented in figure 4 as a function of Reynolds number for the three Mach numbers. These values of C_{D_W} were obtained from graphical integrations of the pressure distributions. In general, the variation of wave drag with Reynolds number for all models at Mach numbers 1.62 and 1.93 is small. The variation at $M = 2.41$ is not as systematic as the variation at $M = 1.62$ and 1.93 but conforms generally to the variation at $M = 1.62$ and 1.93.

In figure 5 the values of the wave-drag parameter are presented as a function of the ratio of base area to maximum area B/S_{max} for several Reynolds numbers at each Mach number. Included for comparison is the theory given by the method of Adams (ref. 1). There is a discrepancy between experiment and theory which becomes greater as Mach number increases and at $M = 2.41$ the experimental values can be as much as 45 percent lower than the theoretical values. Therefore, although the theory predicts no variation in wave drag with Mach number, these results show a Mach number effect that is known to exist for slender bodies of revolution which are not designed for minimum wave drag. Although the body shapes predicted by reference 1 appear to give relatively low wave drag as compared with other body shapes, the theoretical prediction of the drag for these bodies from the same reference is inadequate.

Because of the large inadequacy of the theoretical wave-drag prediction of reference 1 a brief examination was made of this theory. Several values of the theoretical wave-drag parameter calculated by the method of Lighthill (ref. 2) and the method of characteristics for two parabolic bodies of revolution are presented in figure 6 with the theory of reference 1 included for comparison. The method of Lighthill (ref. 2) was selected for comparison with the method of reference 1 since reference 2 utilizes the same basic equation that reference 1 used initially. The first parabolic body of revolution is one having the same base area, maximum area, and length as model 3 used in this investigation. The theoretical wave drag for this body is calculated by the theory given by the method of Lighthill (ref. 2) at Mach numbers of 2 and 4. It is seen that at $M = 2$ the C_{D_W} value calculated for the parabolic body is approximately 1 percent lower than that for the supposedly minimum-drag body of reference 1 and at $M = 4$ the C_{D_W} value calculated for the parabolic body is approximately 26 percent lower than that for the minimum-drag body of reference 1. The second parabolic body of revolution (NACA RM-10) is one which has been employed in many previous investigations and has a fineness ratio of 12.2. The theoretical wave drag for this body is calculated by the method of Lighthill (ref. 2) and by the method of characteristics at Mach numbers 2 and 4. It is seen that for this body the calculated C_{D_W} values are still lower than the values predicted by the theory of reference 1. From the foregoing discussion, it is obvious that the theory presented in reference 1 is inadequate for predicting the shapes of boattail bodies of revolution designed for minimum wave drag, at least for fineness ratios and Mach numbers of practical interest. Furthermore, it was found in the preliminary calculations for this investigation that the equation for drag as minimized in reference 1 (eq. (19), ref. 1) can produce negative drag values and hence can have no minimum.

CONCLUSIONS

An investigation has been conducted in the Langley 9-inch supersonic tunnel to determine the effect of varying Reynolds number and Mach number on the wave drag at zero lift for seven boattail bodies of revolution designed for minimum wave drag according to the method presented in

NACA TN 2550. The tests covered a Reynolds number range of approximately 2.0×10^6 to 10.0×10^6 at each of three Mach numbers, 1.62, 1.93, and 2.41. The following conclusions are indicated:

1. There was little variation in the pressure distribution with Reynolds number.

2. The experimental wave-drag coefficients were less than the theoretical values. The discrepancy increased with Mach number to a value as great as 45 percent of the theoretical drag, whereas the theory predicts no variation with Mach number.

3. According to both the method of Lighthill (R. & M. No. 2003) and the method of characteristics, certain boattail bodies have lower theoretical drags than the bodies whose shapes and drags were found by the method of NACA TN 2550. Thus, the theory of NACA TN 2550 is inadequate for determining the shapes of boattail bodies for minimum drag, at least for fineness ratios and Mach numbers of practical interest. However, the bodies of NACA TN 2550 had relatively low experimental wave drag as compared with other boattail body shapes.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., July 2, 1953.

REFERENCES

1. Adams, Mac C.: Determination of Shapes of Boattail Bodies of Revolution for Minimum Wave Drag. NACA TN 2550, 1951.

2. Lighthill, M. J.: Supersonic Flow Past Bodies of Revolution. R. & M. No. 2003, British A.R.C., 1945.

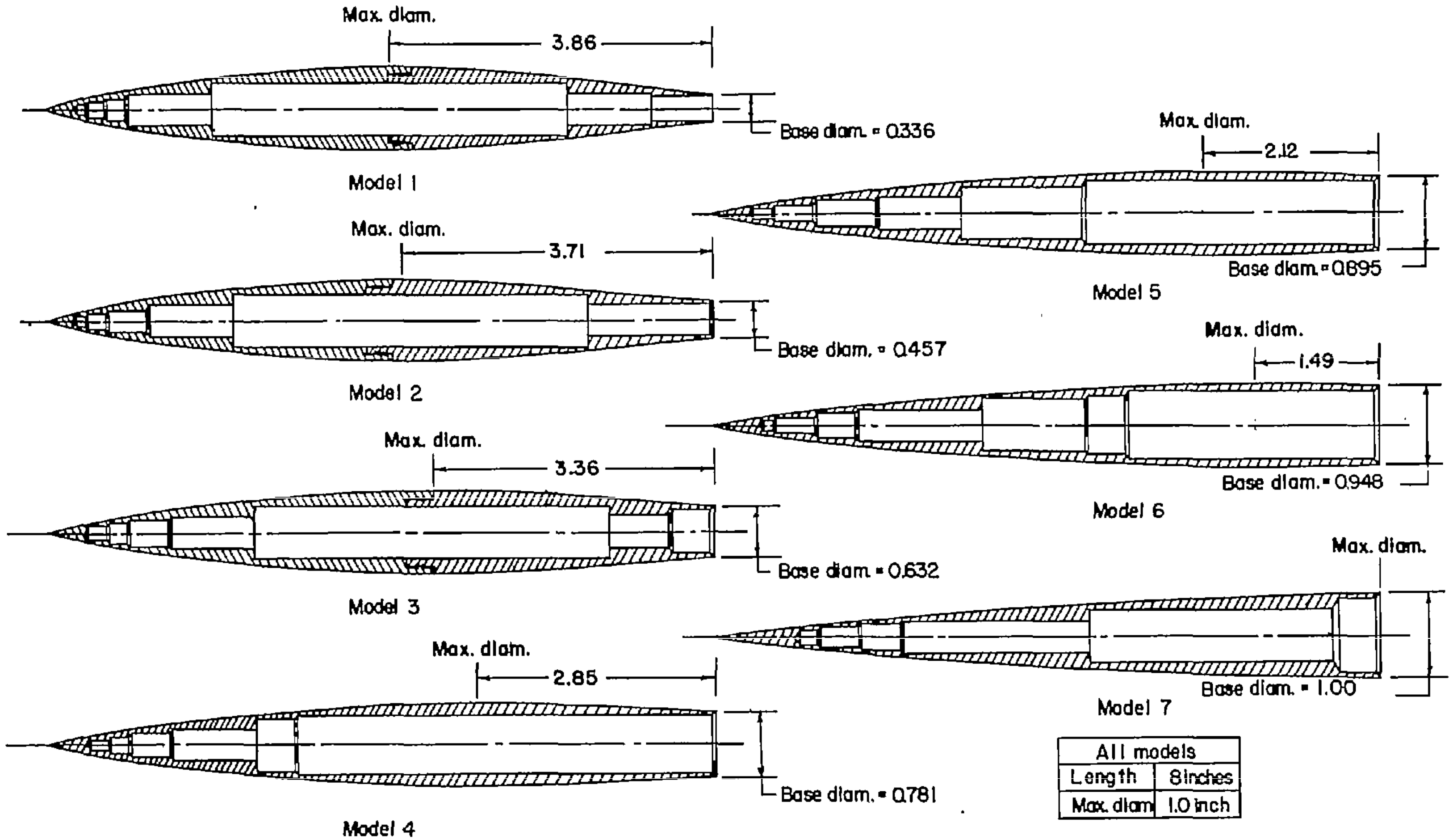

Figure 1.- Drawing of models. All dimensions are in inches.

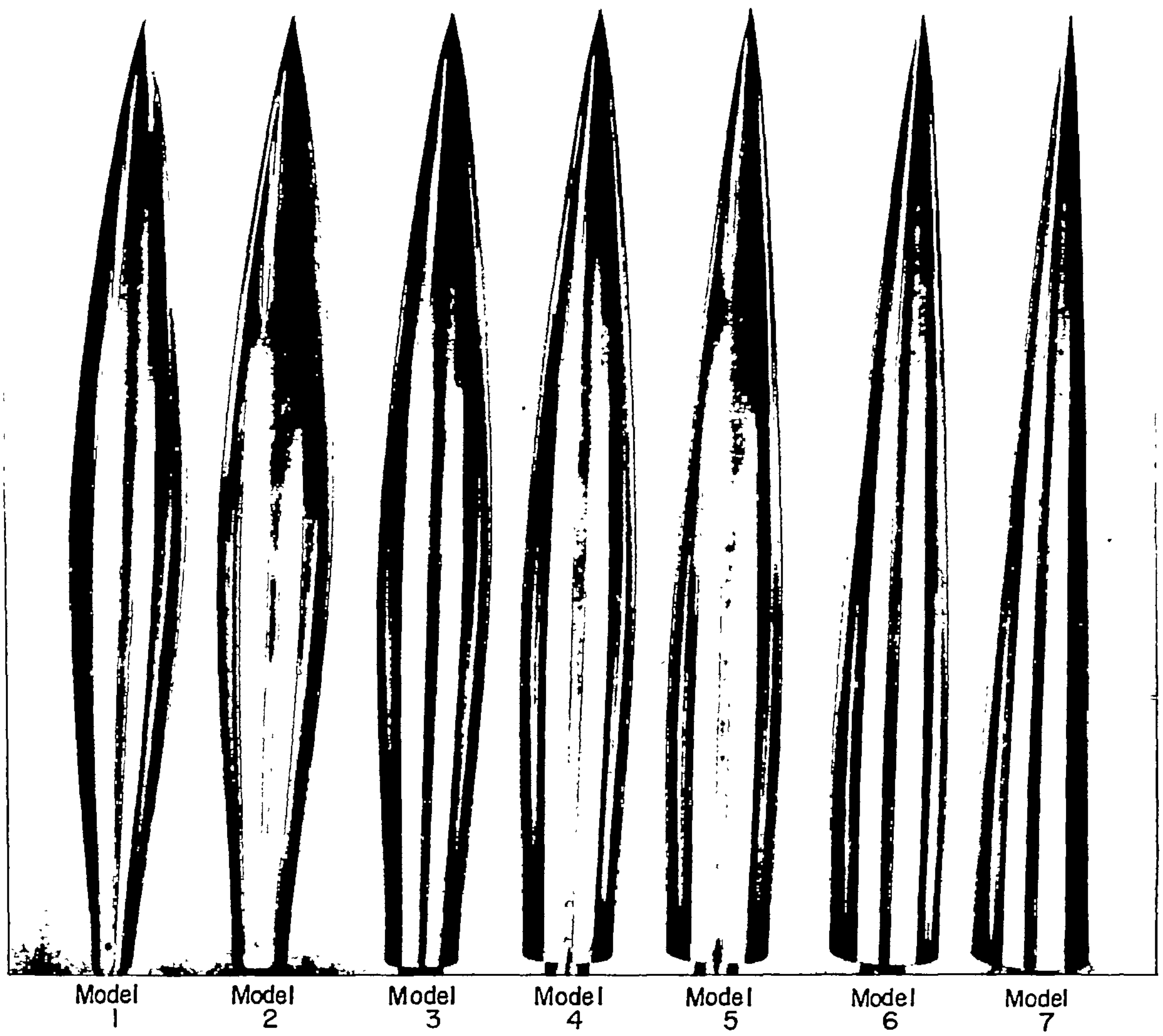

Figure 2.- Photograph of models.

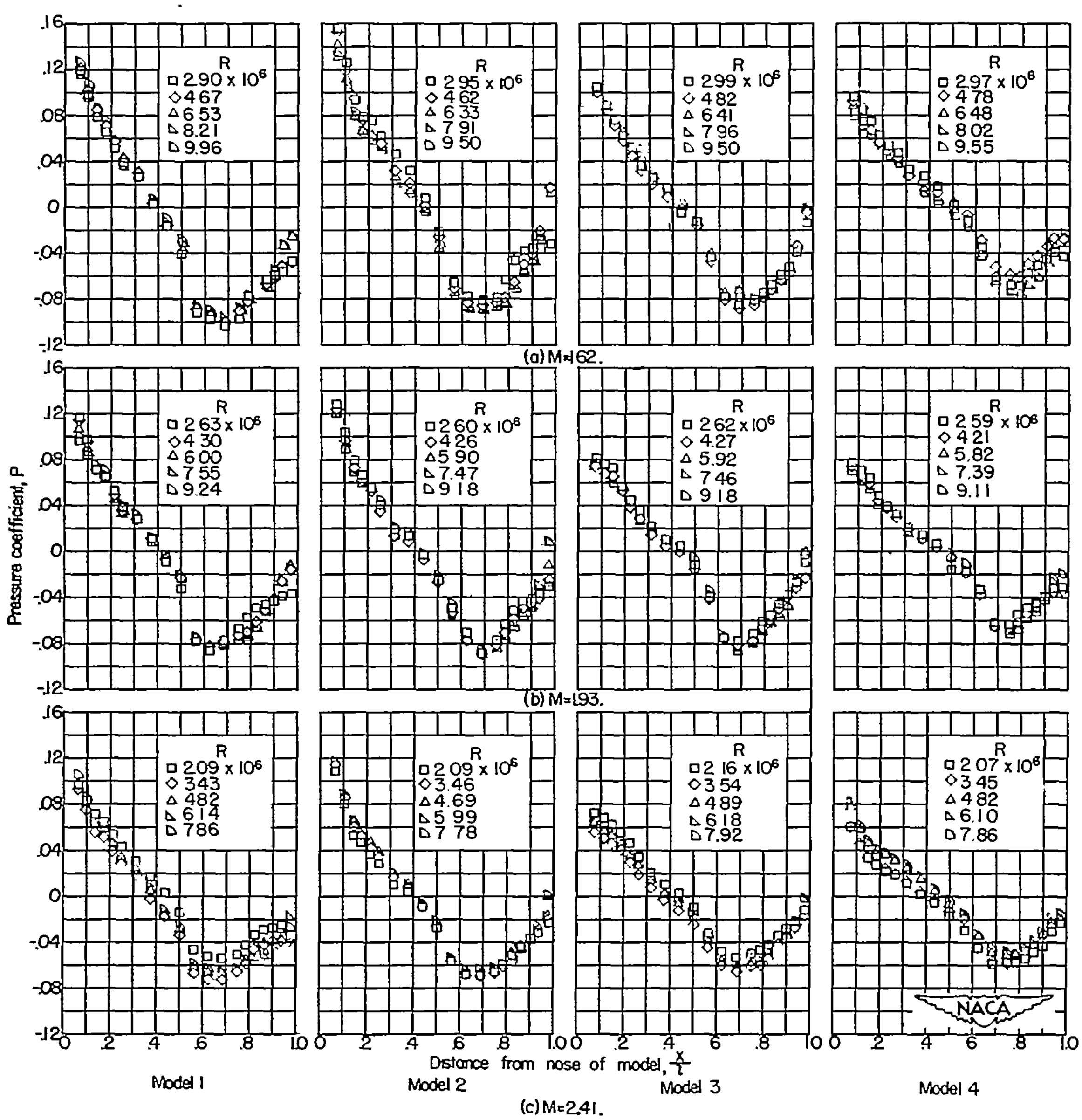

Figure 3.- Longitudinal pressure distributions.

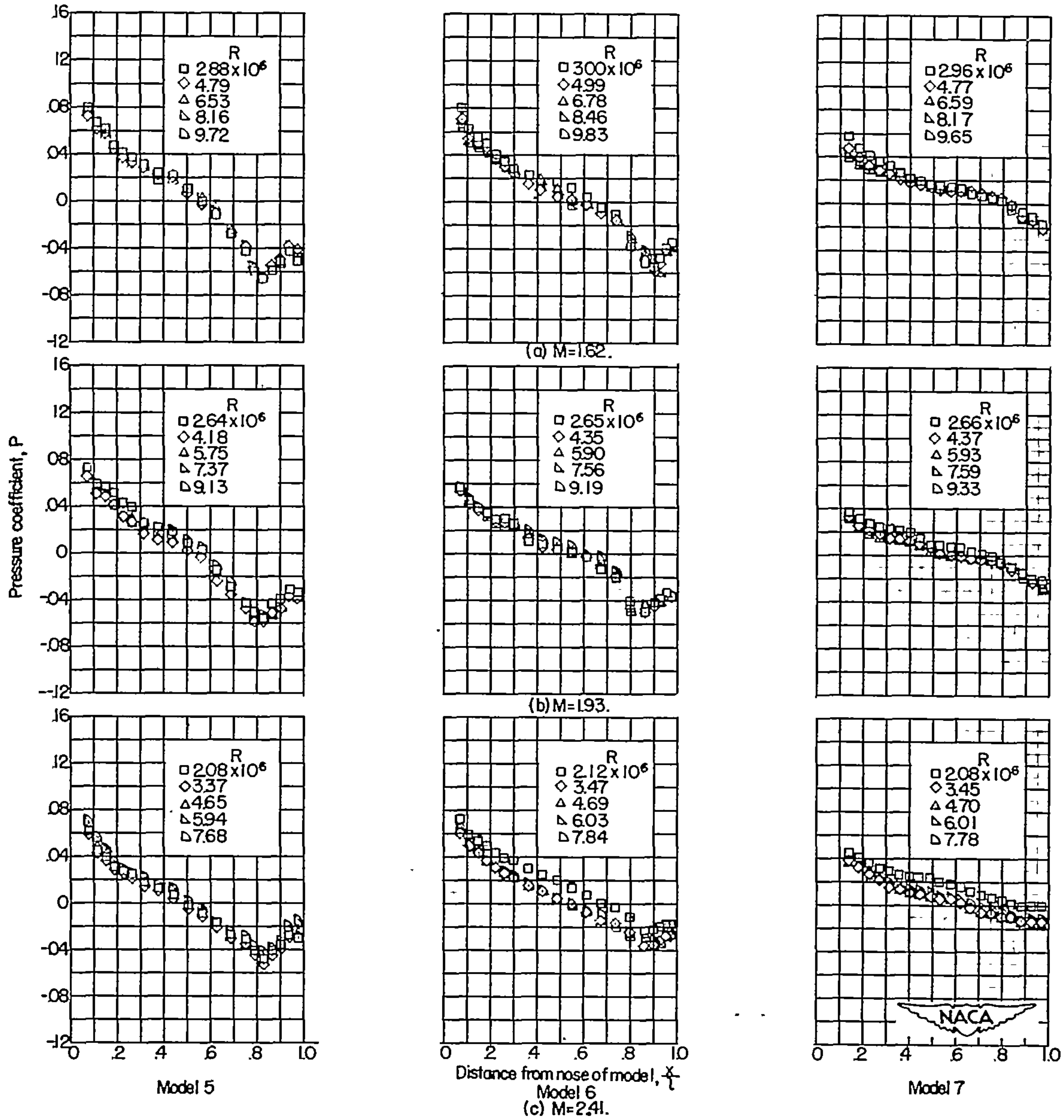

Figure 3.- Concluded.

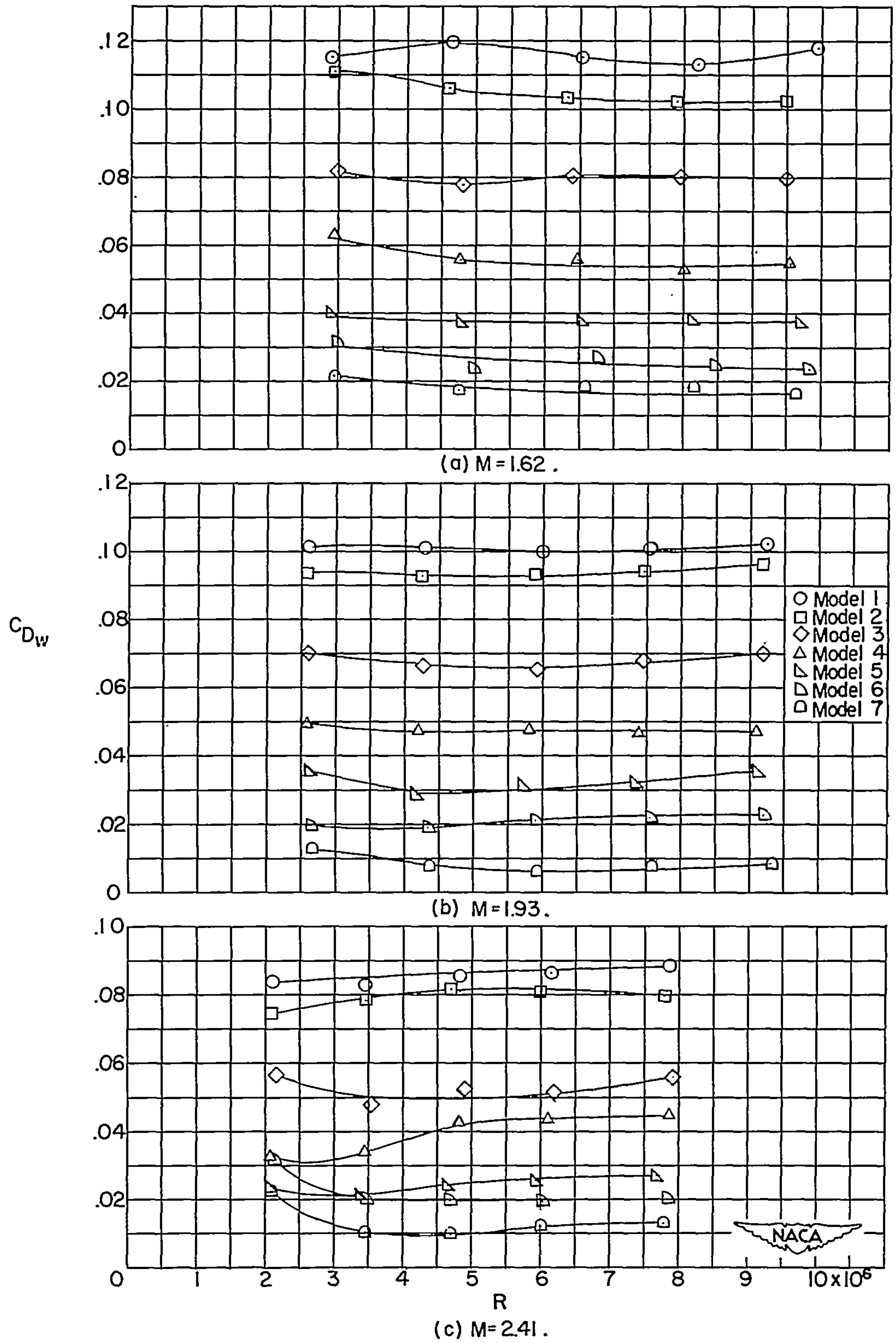

Figure 4.- Variation of wave-drag coefficient with Reynolds number.

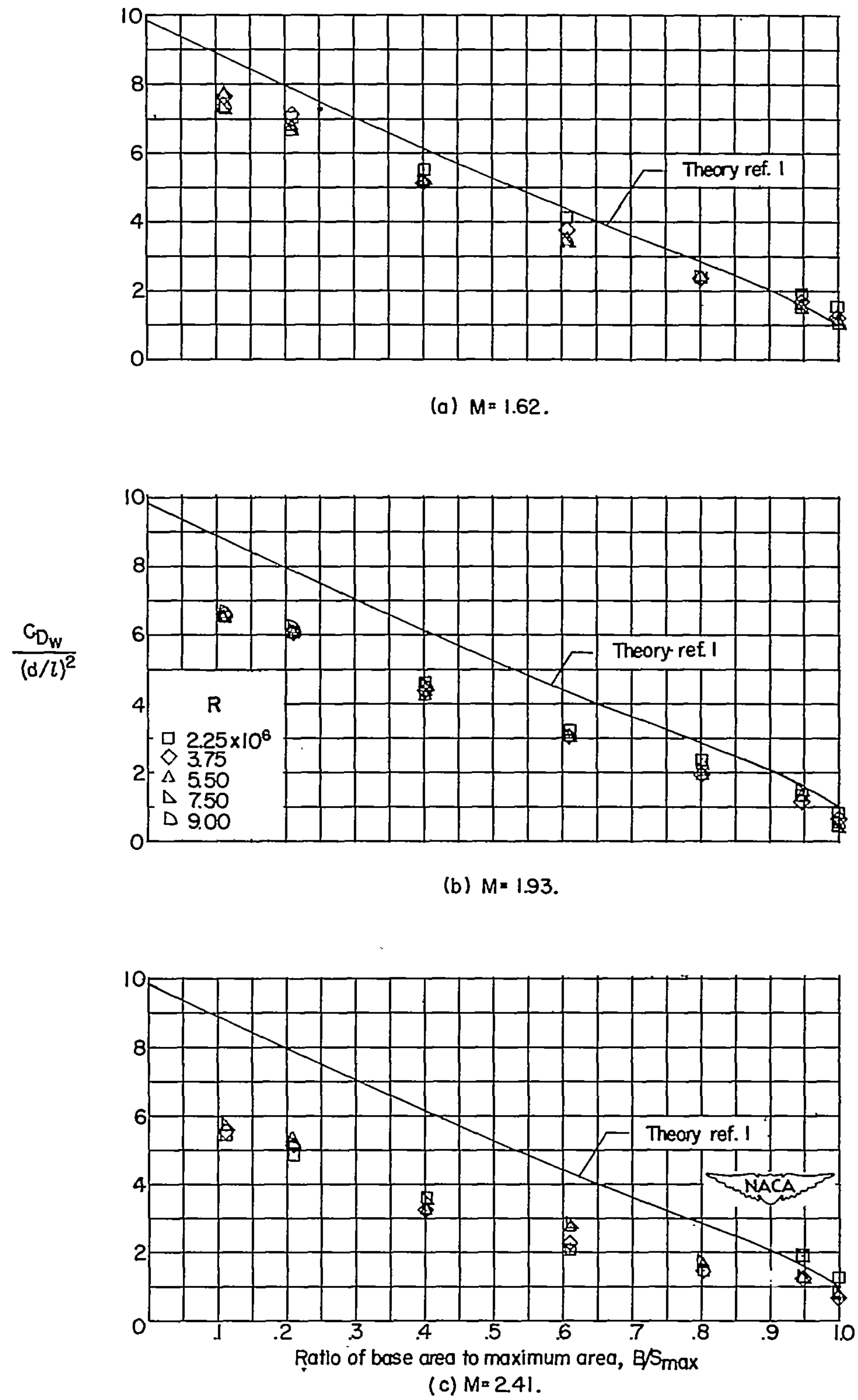

Figure 5.- Variation of wave-drag parameter with the ratio of base area to maximum area.

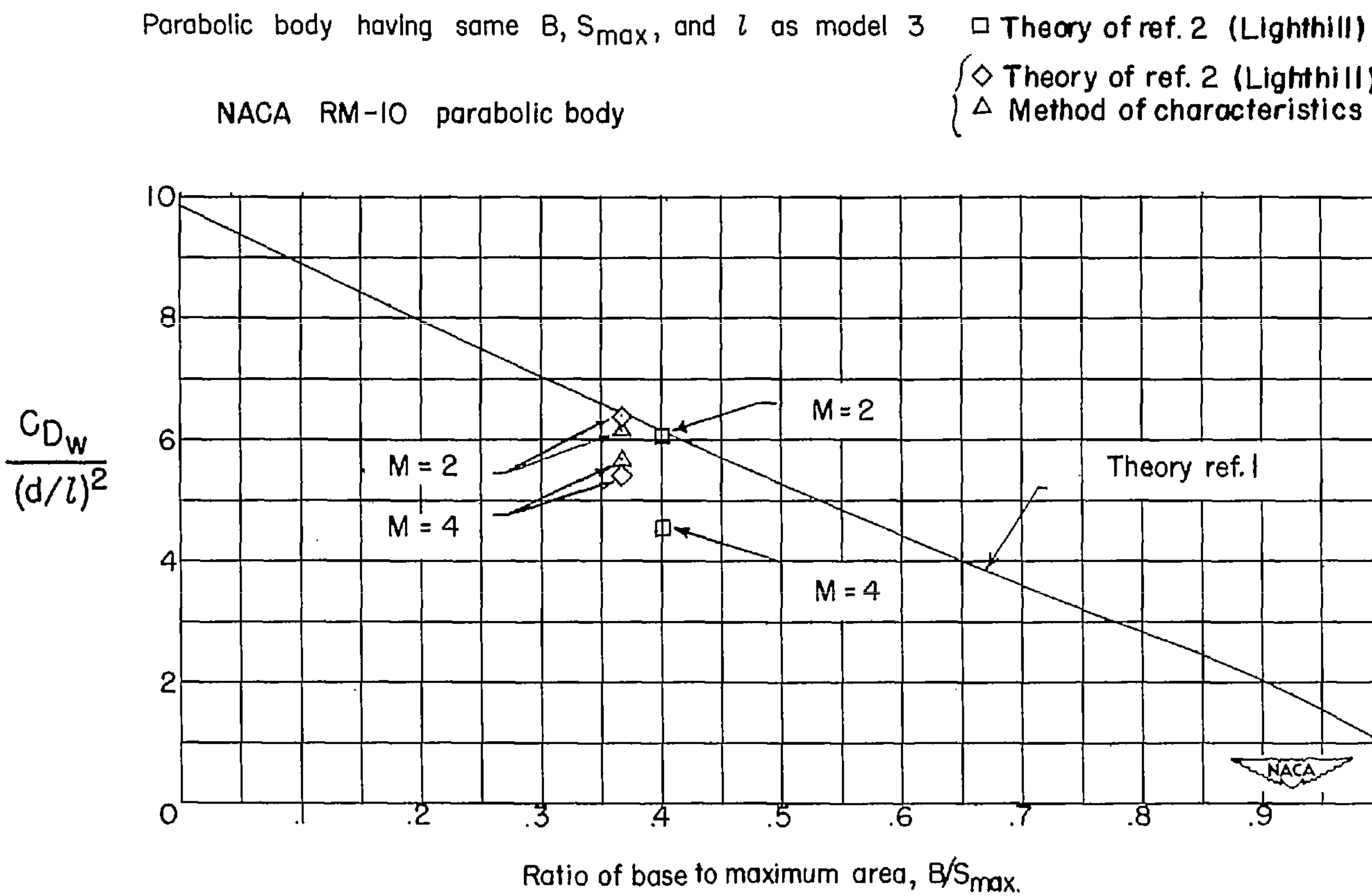

Figure 6.- Variation of theoretical wave-drag parameter with the ratio of base area to maximum area.

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